iRobot

October 16, 2019

Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

Re: *Notice of ex parte filing of iRobot Related to Unlicensed Use of the 6GHz Band, Expanding Flexible Use in the Mid-Band Spectrum Between 3.7 and 24 GHz, ET Docket No. 18-295, GN Docket No. 17-183*

Dear Ms. Dortch:

By this letter, and pursuant to Sections 1.1206 of the Commission's rules,[1] iRobot files this technical study,[2] which provides information on the interference concerns raised by the Commission's proposed rule changes to the 6 GHz band.[3]

As iRobot stated in its September ex parte, we commissioned this technical study to determine specifically the effects of 6 Ghz Wi-Fi routers on iRobot's UWB system.[4] In establishing the parameters for the study, iRobot ensured the parameters were based on very conservative assumptions. For example, the *Technical Study* assumes that video streaming will occur on 160 MHz channels thus having the highest data rates and smallest duty cycles.[5] The *Technical Study* limited the number of routers to one per house. Significantly, it also did not take into account backhaul between routers within the home. Even under these conservative assumptions, the *Technical Study* reveals that interference is "sufficient to disrupt up to 35 percent of UWB ranging signals operating in UWB channel 5 if the Wi-Fi traffic is distributed over all existing and proposed unlicensed channels in 5 and 6 GHz."[6] Such interference levels would "render inoperative" Terra's UWB-based location system.[7]

iRobot recognizes that its findings are not unique to its UWB-based Terra lawnmower. Similar interference levels will be faced by other innovative UWB-based products such as automotive security devices and mobile phones that consumers are using today and will be

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[1] 47 C.F.R. § 1.1206.
[2] *Impact of Proposed High-Power Wi-Fi Operations on Ultra Wide Band Devices at 6 GHz*, prepared by Roberson and Assoc., LLC, Oct. 9, 2019 (*iRobot Technical Study*).
[3] *Unlicensed Use of the 6GHz Band, Expanding Flexible Use in the Mid-Band Spectrum Between 3.7 and 24 GHz*, ET Docket No. 18-295, GN Docket No. 17-183; Notice of Proposed Rulemaking.
[4] Letter from Tonya Drake, Vice President and Asst. General Counsel, iRobot Corp., to Marlene H. Dortch, Secretary, Federal Communications Commission, ET Docket No. 18-295, GN Docket No. 17-183, filed Sept. 17, 2019 (*September Ex Parte*).
[5] *See iRobot Technical Study* at 11.
[6] *Id*. at 15.
[7] *Id*. at 3.

increasingly common in the upcoming years. As the *Technical Study* concludes, and as we offered in our *September Ex Parte*, a coexistence solution is needed to promote innovative radio technologies like UWB and to avoid implicitly dedicating this spectrum to a single technology use case. We remain ready to engage with stakeholders to help develop that solution.[8] Please direct any questions to the undersigned.

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[8] *Id*. at 15.

Roberson and Associates, LLC
Technology and Management Consultants

# Impact of Proposed High-Power Wi-Fi Operations on iRobot Ultra Wide Band Devices at 6 GHz

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**10/14/2019**

**V1.2**

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# 1 EXECUTIVE SUMMARY

The December 17, 2018 Notice of Proposed Rulemaking on Unlicensed Use of the 6 GHz Band (6 GHz NPRM)[1] proposes to permit unlicensed Wi-Fi 6 devices[2] at high power levels, up to 1 W conducted power and 6 dBi antenna gain. The proposed rulemaking would authorize wide deployment of unlicensed devices, including potentially ubiquitous residential deployment, at EIRPs equivalent to +14 dBm/MHz for 160 MHz channels. Unlicensed devices already certified for use in the 6 GHz band utilize Ultra-Wideband (UWB) transmissions for ranging measurements in order to determine precise device location. The Terra™ device manufactured by iRobot relies on precise, UWB-based location as a critical component to accomplish its function as an autonomous lawnmower. The UWB devices employed in the Terra™ lawnmower and stationary beacons transmit and receive signals at very low power levels (EIRP under -41.3 dBm/MHz) to avoid interfering with incumbent licensees in the band. The location determining sub-system employed by the Terra™ system uses UWB channel 5 with a bandwidth of 499.2 MHz and center frequency at 6.4896 GHz.

This report analyzes the interference that will be experienced by victim UWB receivers in iRobot's Terra™ system from Wi-Fi 6 transmitters deployed in nearby residences. The analysis shows that the interference is sufficient to disrupt up to 35% of the UWB ranging/location signals, even if the residential Wi-Fi traffic is distributed over all available and proposed unlicensed channels in the current 5 GHz and proposed 6 GHz U-NII bands. This level of interference is sufficient to disrupt and render inoperative Terra's UWB-based location system. This level of interference is created by Wi-Fi 6 routers deployed at high density in residences in the immediate vicinity of the operation of the Terra™ device, as authorized by the NPRM, and streaming 4K video. If the Wi-Fi traffic is concentrated into three 160 MHz channels that overlap UWB channel 5, then the probability of interference increases up to 80%. Even at 2% router utilization, 10% of UWB ranging signals are disrupted.

Allowing high-power unlicensed devices as proposed by the 6 GHz NPRM will render inoperative any products using UWB for precision ranging and location determination such as employed by Terra™, and currently authorized for use in the 6 GHz band. For this reason, the Commission should reconsider the proposed rules to allow for UWB and Wi-Fi coexistence.

# 2 BACKGROUND

## 2.1 UWB History

Ultra-wideband (UWB) wireless systems are intended for transmitting information over bandwidths much wider than existing licensed services. The transmit Effective Isotropic Radiated Power (EIRP) is low enough to avoid interference with existing services in the same band. The FCC issued its first Report and Order on UWB in February 2002.[3] Since then there have not been any reports of interference with incumbent licensees in the 6 GHz band from UWB transmitters.

[1] FCC, *Unlicensed Use of the 6 GHz Band*, ET Docket No. 18-295, October 23, 2018 (6 GHz NPRM).
[2] Wi-Fi 6 is used as a convenient term for devices that will comply with IEEE Std 802.11ax. See section 2.3 for additional explanation.
[3] See: *First Report and Order* in ET Docket No. 98-153, February 14, 2002.

The IEEE 802.15.4 standard[4] for Personal Area Networks specifies several UWB Physical layers (UWB PHYs). Products use these UWB PHYs in wireless networks for a variety of purposes. One purpose for which UWB devices are very well suited is ranging and location. Because of the extremely wide bandwidths of the UWB signals, time differences corresponding to the propagation delay between a transmitter and a receiver can be precisely measured. Combining these measurements from multiple UWB transmitters produces location estimates with centimeter accuracy. This permits the determination of locations for UWB devices on robots, other objects, or worn by people. Examples of UWB based devices include wireless key fobs for autos, Zebra Technology's NFL Player Tracker, and iRobot's Terra™ autonomous lawnmower.

The IEEE Std 802.15.4 specifies 16 channels for UWB device operations. These have bandwidths of 499.2, 1081.6, 1331.2 or 1354.97 MHz.[5] Three of these UWB channels are within the range of frequencies proposed for new unlicensed uses in the 6 GHz band. These channels are summarized in Table 1 and also depicted in Figure 1. The remaining UWB channels are either not globally available or are collocated with widely deployed high power consumer transmitters (mobile, Wi-Fi, etc.) and are therefore not widely used by UWB devices.

Table 1 UWB Channels in 6 GHz

| UWB Channel | Center Frequency (MHz) | Bandwidth (MHz) |
|---|---|---|
| 5 | 6489.6 | 499.2 |
| 6 | 6988.8 | 499.2 |
| 7 | 6489.6 | 1081.6 |

The FCC rules limit the maximum EIRP for UWB to -41.3 dBm/MHz in a band of frequencies that includes UWB channels 5, 6, and 7.[6]

## 2.2 NPRM Issues Relevant to iRobot Interference Scenario

The 6 GHz NPRM specifies four new unlicensed bands that are named U-NII-5 through U-NII-8. These new U-NII bands span the frequency range from 5925 MHz to 7125 MHz. The new U-NII

[4] IEEE Std. 802.15.4-2015, *IEEE Standard for Low-Rate Wireless Networks*, December 5, 2015 (IEEE Std 802.15.4).
[5] See IEEE Std 802.15.4-2015 Table 16-11 on page 463.
[6] See for example 47 CFR §15.511 (c)

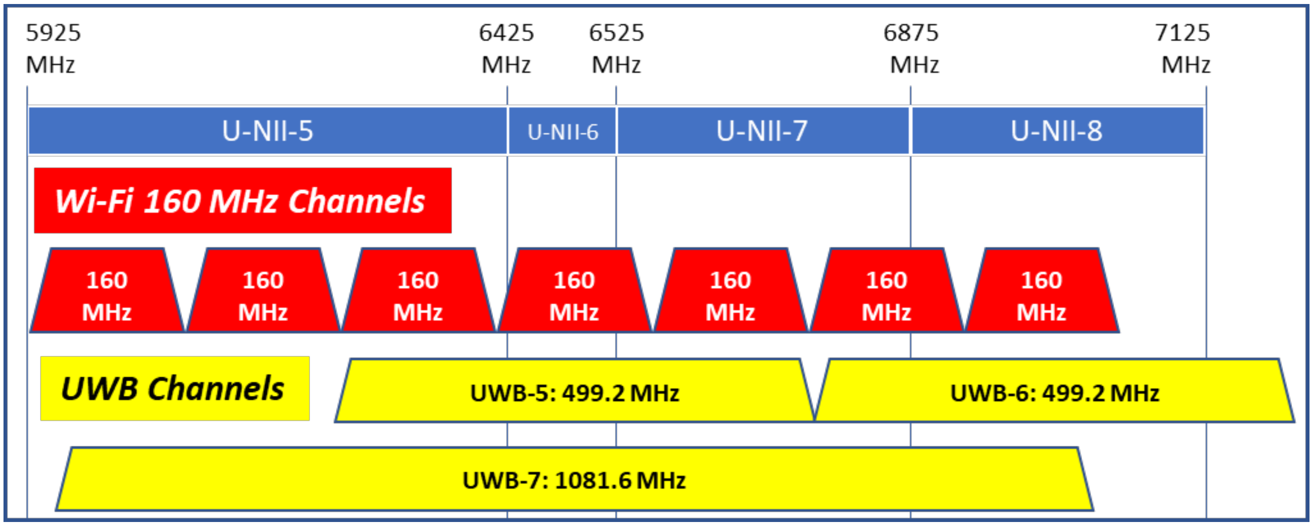


Figure 1 FCC 6 GHz NPRM Spectrum with Wi-Fi and UWB Channels

bands overlap the established UWB channels 5 through 7, as shown in Figure 1. iRobot's Terra™ autonomous lawnmower utilizes UWB channel 5 to determine location.

## 2.3 Unlicensed Wi-Fi: Wi-Fi 6

The Wi-Fi Alliance standardized generational numbering for equipment in 2018. Equipment can indicate that it supports Wi-Fi 4, if the equipment supports 802.11n; or Wi-Fi 5 for 802.11ac; and Wi-Fi 6 for 802.11ax.[7] This report will use Wi-Fi 6 as a synonym for equipment following IEEE Std 802.11ax[8].

### 2.3.1 Wi-Fi 6

The IEEE 802.11 standards organization has proposed new Wi-Fi channels in the 6 GHz band in the IEEE Std 802.11ax. These channels can have bandwidths of 20, 40, 80, or 160 MHz. There is also a specification for combining two 80 MHz channels into a synthetic 160 MHz channel. Three of the 160 MHz IEEE channels overlap UWB channel 5, as shown in Figure 1.

The rules being proposed for the 6 GHz band allow for transmitter power levels up to 1 Watt and antenna gains up to 6 dBi in the U-NII-5 and U-NII-7 bands. Transmit power levels up to 250 mW along with antenna gains up to 6 dBi would be allowed in the U-NII-6 and U-NII-8 bands.

The 802.11ax standard increases the maximum data rates by adding 1024 QAM / OFDM and MU-MIMO to the standard.[9] This permits up to 1.2 Gbps in one spatial stream, and for 8 spatial streams this can multiply up to 9.8 Gbps. This rate is only achieved when the signal to noise ratio is sufficient and 8 antennas are used at both the transmitter and receiver. Very high data rates may

[7] See: *Generational Wi-Fi® User Guide*, Wi-Fi Alliance, October, 2018.

[8] IEEE P802.11ax, *IEEE Draft Standard for Information Technology -- Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks -- Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment Enhancements for High Efficiency WLAN*, anticipated in late 2019, (IEEE Std 802.11ax).

[9] QAM abbreviates Quadrature Amplitude Modulation, OFDM abbreviates Orthogonal Frequency Division Multiplexing, and MU-MIMO abbreviates Multi-User Multiple Input Multiple Output technology. These permit Wi-Fi 6 devices to process simultaneous signals from multiple devices with multiple antennas.

lead to short transmitter duty cycles. Lower data rates correspond to longer transmissions and therefore higher duty cycles for the same information content.

Not all devices or access points will have 8 antennas. Lower cost devices and access points will use fewer streams and therefor have larger duty cycles.

### 2.3.2 Residential Mesh Networks and Extenders

Mesh routers are a popular solution for providing coverage throughout a home. This will lead to situations where the same data is transmitted multiple times over successive hops between routers and finally to the end-point device. This will increase the apparent duty cycle generated by any single end-point device, such as a laptop or a tablet, since traffic for the end-point will be relayed through additional hops to reach the internet. An example residential mesh network is depicted in Figure 2.

A simpler device that is also provided by the industry is an extender for a Wi-Fi network. An extender also relays packets similar to a mesh router, and so it will also increase the apparent duty cycle on the network.

### 2.3.3 Multiband Routers

Some multiband routers will be able to use more than one band at the same time. One band may be used for mesh router-to-router hops while a second band will be used for the end device links. Besides supporting more devices and avoiding interference with other Wi-Fi devices on the same network, multiple bands allows for mesh-to-mesh backhaul without taking away channel capacity from end devices. Figure 2 diagrams a hypothetical residential multi-band mesh network.

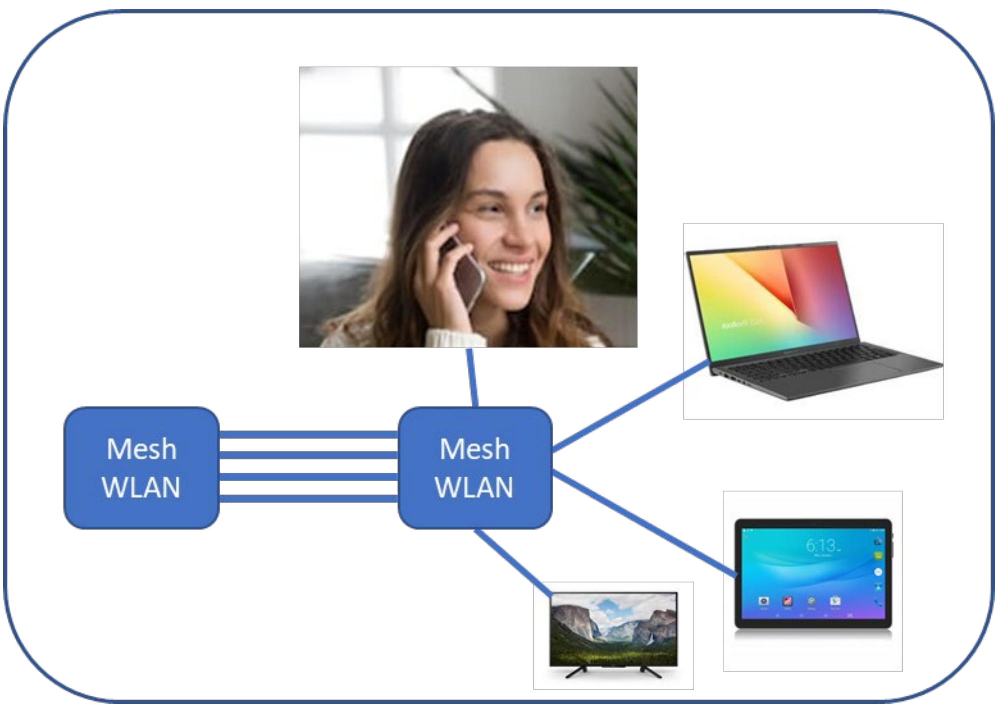


Figure 2 WLAN Mesh Network in a Residence

Even though multi-band routers can minimize interference within the mesh Wireless Local Area Network (WLAN), they can have the opposite effect for victim receivers outside of the network, such as UWB devices. For example, if the end-point devices in Figure 2 used Wi-Fi channels in U-NII-1, the mesh network could relay the messages to (or from) the end-point devices through the mesh network on U-NII-6 channels. This avoids interference on U-NII-1, but it creates interference on U-NII-6. This interference mechanism is included here as a reminder that even if end-point devices do not use U-NII-6, the ubiquitous residential networks envisioned in the 6 GHz NPRM could still use the band and generate interference.

### 2.3.4 Aggregate Power

Wi-Fi interference will be aggregated over in-home and neighborhood device populations. The number of Wi-Fi connected devices in a residence is expected to increase. The FCC anticipates the ubiquitous deployment of Wi-Fi in residences.[10]

## 2.4 Wireless Uses and Traffic

### 2.4.1 Streaming Video 4K, 8K

A quick survey of televisions for sale to consumers from retailers such as Costco shows that they are all 4K or UHDTV.[11] [12] The usual implication is that horizontal resolution is about 4,000 pixels. By November 2017, both Microsoft and Sony had released game devices that support 4K streaming and gaming.[13] [14] The industry has numerous other products with 4K displays for internet use.[15] [16] [17] [18] Some 8K video is becoming available and may be popular in the future.[19] [20]

Providers of 4K video recommend bit rates of 15 Mbps to 45 Mbps, depending on the provider, and their preferred video codec technology. The recommended data rates[21][22][23] are tabulated in Table 2. The Duty Cycle is then calculated with a ratio for the given bit rate.

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[10] See *FCC 6 GHz NPRM*, Introduction: "Meanwhile, lower powered indoor operations – which we anticipate will be dominated by devices deployed ubiquitously inside homes and businesses – would be permitted to operate in two other sub-bands (totaling 350 MHz of spectrum)."
[11] Costco, TVs, https://www.costco.com/televisions.html
[12] The UHDTV1 spec is for 3840 x 2160 pixels, and this is usually considered to be 4K. The UHDTV2 spec double the horizontal and vertical pixels so it would be considered 8K. Another term that is often used 2160p which comes from the vertical resolution of the UHDTV1 spec.
[13] Microsoft, Xbox One X, https://www.xbox.com/en-US/xbox-one-x
[14] Sony, PS4 Pro, 4-K Gaming TV and More, https://www.playstation.com/en-us/explore/ps4-pro/
[15] Charles Cheevers, Arris, *The Quest to Send 4K Video Over Wi-Fi Networks*, 2014, https://www.arris.com/globalassets/resources/white-papers/arris_quest_4k_video_over_wi-fi_wp.pdf
[16] Best Buy, 4K Ultra HD Connected Home, https://www.bestbuy.com/site/4k-ultra-hd-ecosystem/4k-ultra-hd-connected-home/pcmcat748301862624.c
[17] Amazon, Fire TV Stick 4K with Alexa Voice Remote, streaming media player, https://www.amazon.com/Fire-TV-Stick-4K-with-Alexa-Voice-Remote/dp/B079QHML21/
[18] Apple, Apple TV 4K, https://www.apple.com/apple-tv-4k/.
[19] Stewart Wolpin, *What You Can Expect from 8K TVs in 2019*, January 2019, https://www.techlicious.com/blog/8k-tv-ces-2019/
[20] YouTube, How to Download 8K Video from YouTube, https://www.4kdownload.com/howto/howto-download-8k-video-from-youtube
[21] Internet Connection Speed Recommendations, https://help.netflix.com/en/node/306
[22] Watch Video in 4K Ultra HD on Your Fire TV, https://www.amazon.com/gp/help/customer/display.html?nodeId=201859000
[23] Recommended upload encoding settings, https://support.google.com/youtube/answer/1722171?hl=en

Table 2 Video Duty Cycles

| Provider | 4K Recommended Rate (Mbps) | Duty Cycle at 250 Mbps | Duty Cycle at 1000 Mbps |
|---|---|---|---|
| You Tube | 35-45 | 14-18% | 3.5-4.5% |
| Amazon | At least 15 | 6% | 1.5% |
| Netflix | 25 | 10% | 2.5% |

The values in Table 2 show that the duty cycle for a 4K video streaming AP can range from 6% to 18% if the Wi-Fi channel and Wi-Fi router's capabilities can only support 250 Mbps. If the Wi-Fi channel can support 1000 Mbps and the Wi-Fi router is able to transmit at 1000 Mbps then the duty cycles will range from 1.5% to 4.5%. With four times the number of pixels compared to 4K video, 8K video will need even larger Duty Cycles.

# 3 UWB Location Technology

The location of UWB devices is found by ranging measurements from devices that are stationary in known locations. Ranging measurements are described in the following sub-section.

## 3.1 Ranging

UWB utilized for ranging can be accomplished between two devices by exchanging, 2, 3, or 4 messages; measuring the round trip and delay times for each message; and then averaging the results in some way to determine a propagation time. This report will only consider a ranging method that exchanges 3 messages because it minimizes the number of messages and the measurement errors. Ranging with a sequence of three transmissions will measure time-of-flight or propagation delay time, $T_{prop}$, and then communicate the time-of-flight data to one UWB device. Corrupting any one or more of the three transmissions will obstruct the measurement. The transmission and reception of the three transmissions is shown in Figure 3.

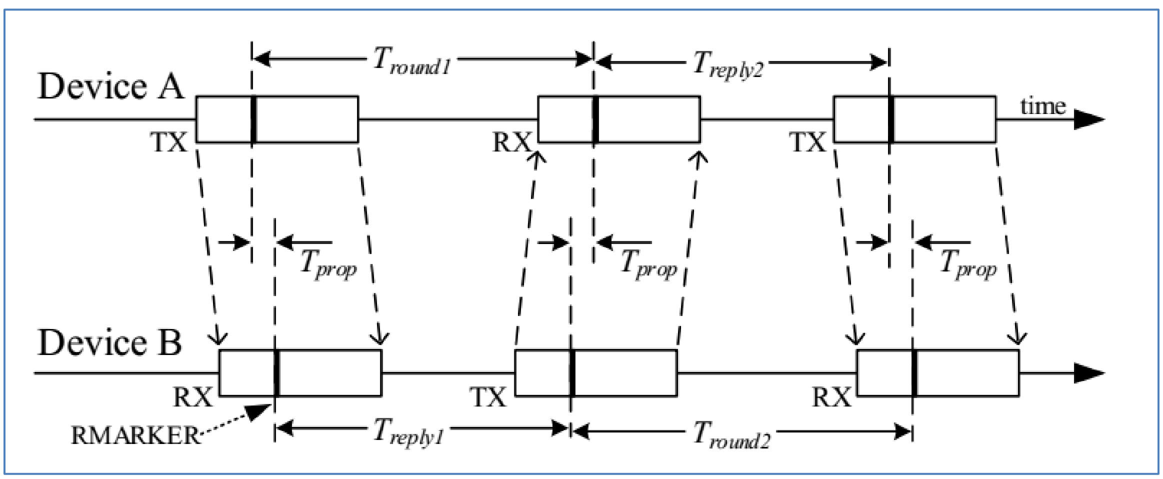


Figure 3 UWB Ranging Messages

The Figure shows an initial transmission from Device A to Device B with propagation delay time $T_{prop}$. Following the first message, Device B then transmits a response back to Device A with the same propagation delay time, $T_{prop}$. Device A then follows with a third transmission back to Device B, again with delay time $T_{prop}$. Device A can measure the first-round-trip-time as given in Equation

1.

$T_{round1} = T_{reply1} + 2\ T_{prop}$ Eq. 1

Device A can also measure $T_{reply2}$. The third message in the sequence can include both $T_{round1}$ and $T_{reply2}$ so that Device B will know both of those time intervals. Device B can also measure both $T_{reply1}$ and the second-round-trip time as given in Equation 2.

$T_{round2} = T_{reply2} + 2\ T_{prop}$ Eq. 2

At the end of the 3 messages, Device B can add together equations 1 and 2 to average out some systematic timing errors, and then solve for $T_{prop}$ to obtain Equation 3.

$T_{prop} = \frac{1}{4} (T_{round1} - T_{reply1} + T_{round2} - T_{reply2})$ Eq. 3

Another solution for $T_{prop}$ is given in Equation 4. Either equation 3 or 4 may be used since they both give the same result if the time measurements are very accurate. If the time measurements have any precision errors, then Equation 4 is preferred because it minimizes errors in $T_{prop}$.

$$T_{prop} = \frac{T_{round1}\, T_{round2} - T_{reply1}\, T_{reply2}}{T_{round1} + T_{round2} + T_{reply1} + T_{reply2}} \quad \text{Eq. 4}$$

Device B knows all the measured quantities on the right side of the equation so it can easily calculate $T_{prop}$. The propagation distance is then easily computed by multiplication with the speed of light, c.

$D_{prop} = c\ T_{prop}$ Eq. 5

# 4 INTERFERENCE SCENARIOS

## 4.1 Interference Criterion and FCC Perspective

Receiver interference characteristics are common standard figures of merit for comparison of different equipment from different manufacturers. A typical example is co-channel interference rejection, as defined in the TIA-102.CAAA standard, excerpted below, or the TIA-603 standard which defines a similar figure of merit.[24] A 3 dB threshold is also used in the IEEE Std 802.15.4.

> *The co-channel rejection is the ratio of the reference sensitivity to the level of an unwanted input signal. The unwanted signal has an amplitude that causes the BER produced by a wanted signal 3 dB in excess of the reference sensitivity to be reduced to the standard BER.*

Decawave, the supplier of the UWB location subsystem components used in Terra™, has established a 3 dB threshold for interference degradation. This is the identical threshold used in the Decawave analysis of interference submitted in a comment on the FCC NPRM for 6 GHz.[25] One example from the Decawave analysis is excerpted below.

> *Based on measurements performed for ETSI, the red line at -78 dBm corresponds to the power level at which RLAN interferers cause 3 dB sensitivity reduction.*[26]

[24] See: ANSI-TIA-102.CAAA-D, Clause 2.1.8.1, Co-Channel Rejection Definition; and also ANSI-TIA-603, Clause 2.1.21.1, Blocking Rejection Definition.

[25] See: FCC 6 GHz NPRM, Comments of Decawave, February 15, 2018, Annex A, Section 2.1, Single interferer separation distance, page 12, and again in Section 2.2 and Section 2.3.

[26] ETSI is an abbreviation for the European Telecommunications Standards Institute. RLAN is an abbreviation used in Europe for Radio Local Area Network. It is synonymous with a Wireless Local Area Network (WLAN) that is commonly used in the US and in this report.

## 4.2 Interference Threshold

A reduction in sensitivity of 3 dB will occur if the noise floor is increased by 3 dB. Another way to express this is with a noise rise measurement ($N_{rise}$). If the noise rise is 3 dB, then the victim receiver sensitivity is reduced by 3 dB. The Link Budget given in the Appendix shows the noise floor ($N_0$) to be -111.79 dBm/MHz, and it also shows an interference power (I) nearly equal to the noise floor to obtain a noise rise ($N_{rise}$) of 3 dB. This value for the interference power ($I=N_0$) will be used in the simulation described in the next section as the interference criterion.

# 5 ANALYSIS APPROACH

This report presents Monte Carlo simulation results for interference from neighborhood Wireless Local Area Network (WLAN) Access Points (APs) to UWB victim receivers to estimate the probability of interference. The Monte-Carlo simulation created a neighborhood of homes with rectangular yards and rectangular house footprints. WLAN APs were placed randomly inside each house footprint and UWB victim devices were placed randomly in the yard area exterior to the house footprint. The AP transmissions were modeled as bursts in streaming video links to a television or computer as shown in Figure 4. The burst model was used to emulate the buffer drawdown and buffer refill dynamics of streaming video. A fraction of available access points were then randomly marked as either active or non-active to model the likelihood that streaming video was taking place in a house. The video burst duty cycles were varied to model the effect of different video data rates and WLAN data rates. A simplifying assumption was made that the buffers were refilled four times a second resulting in a 250 ms simulation interval. The timing offset of the buffer refills in the simulation interval was randomly assigned. The ranging triplet of UWB signal packets was placed at a fixed offset within the simulation interval. This arrangement is shown in Figure 4.

Each of the simulation conditions included 200 instances for 200 random AP and UWB receiver locations. This results in 40,000 Monte Carlo runs for each condition. The average rate of UWB ranging sessions was assumed to be two times per second and that as many as four UWB receivers would be in range. The simulation included 2 ranging sessions active in each simulation interval.

An interference event is defined as occurring when the received power from an AP exceeded an interference threshold (see section 4.2) and the WLAN streaming video burst overlapped in time with one or more of the three ranging packets. The number of interference events was counted over the entire simulation.

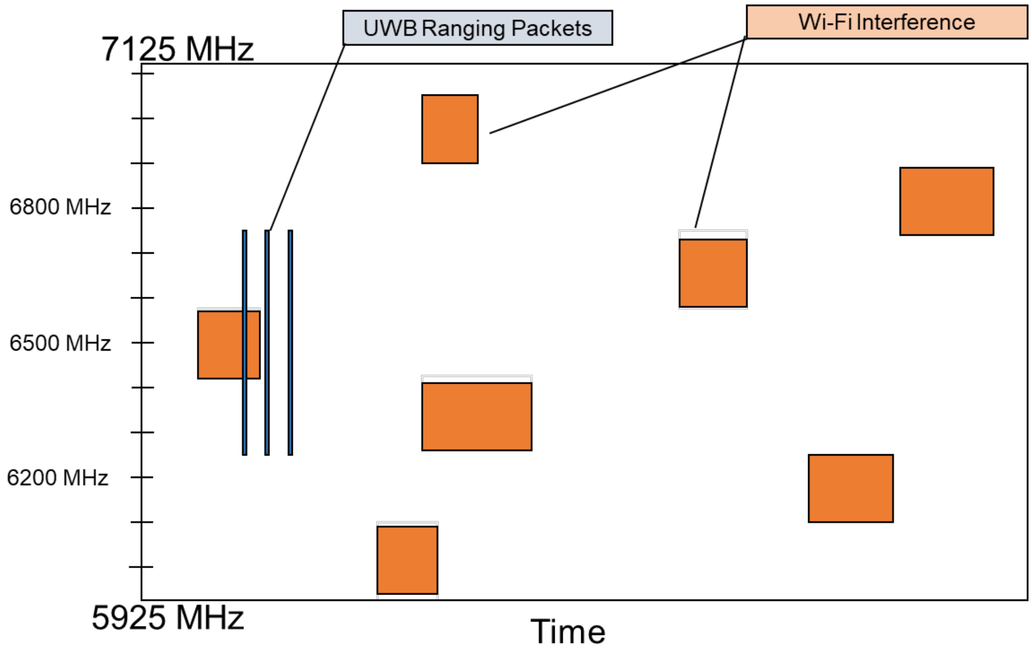


Figure 4 Wi-Fi Interference with UWB Measurement of $T_{prop}$ Shown in Time x Frequency

## 5.1 Wi-Fi Access Point Characteristics

The Wi-Fi 6 APs were assumed to be able to support very high data rates needed for streaming 4K or better video quality. Only one AP was assumed to be in use in each residence if that residence was active. Mesh and multiband router configurations were not simulated.

### 5.1.1 Power Levels

The indoor APs were assumed to transmit at 1 W except for APs that overlapped the U-NII-6 band. The transmit power levels for APs in U-NII-6 were set to 250 mW. The transmitter antenna gain was set to 0 dBi.

In addition to the indoor APs an outdoor AP was also assumed to be present. One outdoor AP among the 49 possible indoor APs in the 7x7 grid is a 2% fraction of outdoor APs (see Figure 5). The 6 GHz NPRM permits outdoor deployment of APs in the U-NII-5 and U-NII-7 bands. The Wi-Fi industry currently sells various consumer devices, including APs, for outdoor deployment.[27]

### 5.1.2 Propagation

The simulation used an NLOS propagation model with 11 dB BEL from the indoor AP transmitters to the victim UWB device. This is a conservative estimate of path loss that includes scattering obstacles between the transmitter and receiver.

The outdoor AP used the LOS propagation model and no building entry loss.[28]

[27] Best Buy, https://www.bestbuy.com/site/searchpage.jsp?id=pcat17071&st=outdoor+wifi

[28] LOS abbreviates the Line-of-Sight propagation model, while NLOS abbreviates Non-Line-of-Sight. BEL abbreviates Building Entry Loss. See Appendix sections 7.2 and 7.3 for more information.

### 5.1.3 Activity and Duty Cycle Conditions

The simulation conditions varied the video streaming burst in seven duty cycle values between 0.44% and 10%. The conditions also varied over a range of twenty AP activity levels (percent of residences streaming video) from 5% to 100%. This comes to a total of 5.6 million Monte Carlo runs in the simulation.

## 5.2 Spectral characteristics

Simulations used the very conservative assumption that all video streaming takes place on 160 MHz channels having the highest data rates and therefor the smallest duty cycles. Two models for the distribution of Wi-Fi channels were simulated. In the first model a 160 MHz channel was randomly selected from a pool of 11 possible channels where 7 were in the proposed new 6 GHz Wi-Fi bands and 4 were in the existing 5 GHz Wi-Fi bands. In the second model a 160 MHz channel was randomly selected from one of the three 160 MHz channels that overlap the 499.2 MHz UWB channel 5 centered at 6489.6 MHz (see Figure 1).

## 5.3 Temporal characteristics

Video streaming over the internet uses buffering at the viewer to prevent network congestion and other sources of error from causing incomplete or dropped video frames. WLAN packet traffic during sample video streaming sessions have been observed, and it was found that there were intervals of about a quarter of a second or more between bursts of large numbers of 1500-byte video data packets. The data rates peaked during these bursts. The duration of the buffer refill bursts was calculated based on assumptions regarding likely video streaming rates. A buffer refill interval of a quarter of a second was selected for the simulation. One refill was assumed to take place at a random time during each simulation interval.

Assuming that all potential interference transmissions used 160 MHz channels also implies that the shortest duty cycles will be observed. Transmitting the same data over 80 or 40 MHz channels will double or quadruple the duty cycles, and increase the probability of interference proportionately.

Other Wi-Fi transmissions besides video streaming were not included in the simulation. These include TCP handshakes, DNS requests, ARP requests, and others.[29] All of these can also interfere with UWB ranging messages.

## 5.4 Simulation of Interference in Residential Neighborhood

The neighborhood simulation was performed over a 7x7 grid shown at the left in Figure 5. A close-up view of the central 3x3 sub-grid is also shown on the right. All nine possible interference signals seen by the UWB receiver are shown in the close-up view. The neighborhood lot size was 1000 square meters which is close to ¼ acre. The Census Bureau Survey of Construction in 2015 had a median lot size of ¼ acre, and so this was selected for the simulation.[30]

[29] TCP abbreviates Transmission Control Protocol, DNS abbreviates Domain Name System, and ARP abbreviates Address Resolution Protocol. Collectively these are network functions that provide useful internet service. They require 2-way traffic interactions over the network.

[30] See: *Survey of Construction*, Census Bureau, 2015

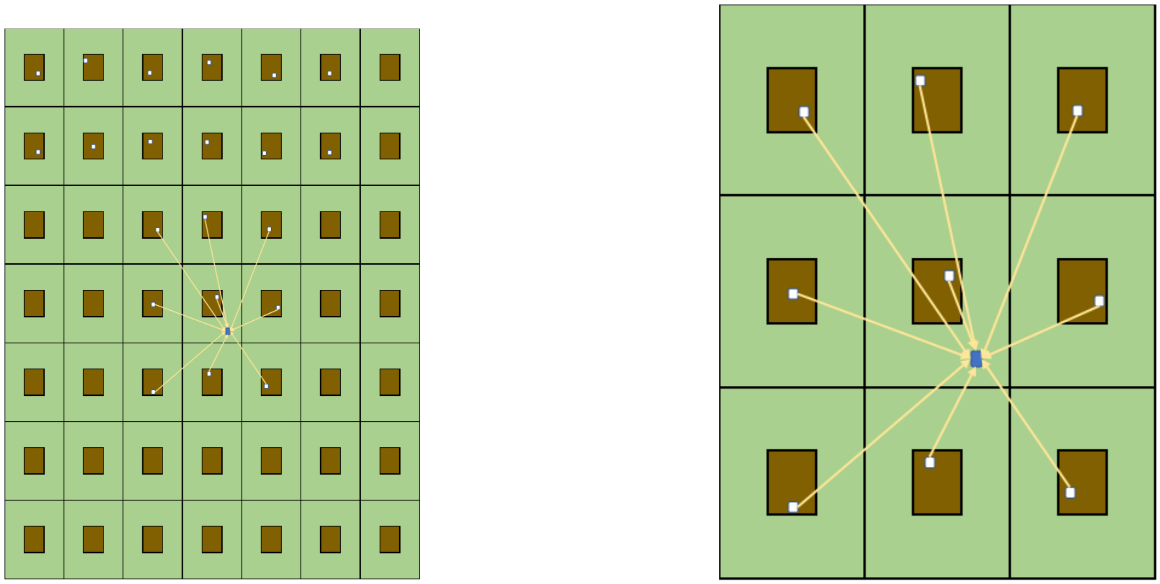

Figure 5 Simulation Arrangement of Residential Lots

Each lot has dimensions of 22.5 m by 45 m. The entire 7x7 grid then covers an area with dimensions of 157.5 m by 315 m.

## 5.5 Calculation of Interference within Simulation

The probability of interference is calculated in the Monte Carlo simulation by randomly varying the locations and activations of the APs in the simulation and the victim UWB receiver. Each activated AP then generates message bursts to simulate the duty cycle in the condition, on one of the Wi-Fi channels in the simulated condition. The path losses are then computed for each and a decision is reached on whether interference with the victim receiver will occur. The decision is reached by comparing the time interval and frequency interval of the AP transmission with the corresponding time x frequency parameters for the ranging bursts at the victim receiver. The number of interfering trials is summed and divided by the total number of trials (40,000 for each condition) to estimate the probability of interference. This estimates the probability of interference for at least 1 ranging burst of 3 packets.

## 5.6 Results

The simulation results are summarized in Figure 6. Additional details are explained in the Appendix.

Figure 6 shows the average probability of interference over all the conditions for AP duty cycles up to 10% and AP activity up to 100%. The AP activity represents how many APs in the simulation are transmitting data traffic at the given duty cycle (up to 10% duty cycle). The AP traffic is distributed across the 5 GHz and 6 GHz bands, so only about 27% of the traffic overlaps UWB channel 5, as is shown in Figure 1. The probability of interference increases up to 35% for the 10% duty cycle and 100% AP activity.

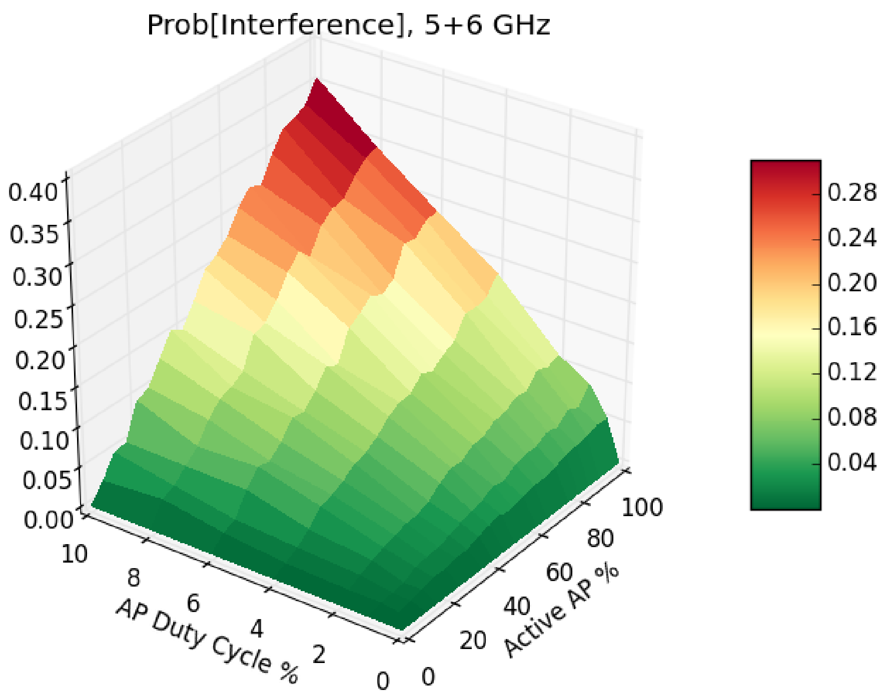


Figure 6 Probability of Interference for Wi-Fi Traffic Distributed Across 5 and 6 GHz U-NII Bands

This simulation result applies to the scenario that the entire 6 GHz band is opened to unlicensed operation as expressed in the 6 GHz NPRM. If only some portion of the band is opened, then the traffic would necessarily concentrate there and the probability of interference would have to be adjusted according to the overlap with UWB channel 5.

Some convenient assumptions in the simulation have been made that have minimized the interference probability result. Some of these assumptions may be broken in some neighborhood deployments.

(a) Wi-Fi 6 transmissions are all assumed to be 1 Gbps. This is close to the maximum standard value of 1.2 Gbps for a single spatial stream. Previous experience suggests that most equipment will be unable to achieve the maximum bit rate in actual operation. Lower bit rates will force higher duty cycles to provide acceptable services, and this will result in higher interference probabilities for victims such as UWB receivers.

(b) Wi-Fi 6 transmissions use 0 dBi transmit antenna gain. The 6 GHz NPRM permits up to +6 dBi of gain, so interference could be up to 6 dB higher power.

(c) Wi-Fi 6 transmissions are distributed across available 5 GHz and the additional 6 GHz bands in the NPRM. This dilutes the interference in UWB channel 5 down to 27%. If the traffic is concentrated in sub-bands that overlap UWB channel 5, then interference increases proportionately. Figure 10 in the Appendix shows the probability of interference can reach 80% if all the traffic is concentrated into channels that overlap UWB channel 5.

(d) Wi-Fi 6 transmissions are limited to a single AP in a residence (or one AP outdoors). The trend to mesh networks with multiple APs would necessarily increase interference. Similarly, only one outdoor AP was simulated. Trends to increase outdoor devices would also cause increased interference.

(e) Non-Line-of-Sight (NLOS) paths are used for the interference path, which results in more attenuation of interference signals. If Wi-Fi 6 devices are deployed at higher elevations, such as a second story in a residence, then the LOS model may apply and additional interference could result.

(f) The neighborhood in the simulation used ¼ acre lots (1000 $m^2$). However, half the construction surveyed by the Census Bureau was for small lots, which would increase the geographic density of ubiquitous AP devices. This would lead to shorter distances, lower path losses, and therefore higher interference powers at the victim.

(g) The simulation provides a probability of interference for a single ranging signal, and not an entire operational system. A typical location system will measure ranges to determine locations many times a second for the system devices, such as robots or people wearing a location device, as the devices move around in real time. While momentary disruptions may be tolerated, persistent and chronic disruption would occur for services such as video programs that may last for an hour or more. The result would lead to unknown location information, system failure, and shutdown.

(h) A location system relies on Beacons at fixed locations (see Figure 7 in the Appendix) that can also be victims of Wi-Fi interference. The interference paths to the Beacons will be independent of the paths to a moving robot, and the probability of interference will be independent as well. The cumulative probability of failure will tend to sum over all the beacons and devices in the system, for example it would be approximately 5x for a hypothetical example shown in Figure 7.

(i) Out-of-Band-Emissions (OOBE) from interfering transmission were not considered in this simulation. The Wi-Fi 6 interfering transmissions are about 55.3 dB more powerful than desired UWB transmissions when the Wi-Fi 6 channel and UWB channel overlap. This is such a high power differential that even a Wi-Fi 6 device on another channel in the 6 GHz band will still generate enough interference to create degradation of the UWB system. The 6 GHz NPRM places a limit on outside the band (OOBE) at -27 dBm/MHz. This is still 14.3 dB higher than the power limit of UWB devices, and so it will still destructively interfere.

# 6 Summary and Conclusions

6 GHz band incumbents currently include unlicensed UWB devices that are used for ranging measurements in order to determine device locations. These UWB devices transmit and receive signals at very low power levels (EIRP under -41.3 dBm/MHz) to avoid interfering with licensees in the band. Technical analysis shows that these existing authorized and certified unlicensed devices will be subjected to interference that will render them inoperative if high-power unlicensed Wi-Fi devices are deployed as proposed by the December 2018 Notice of Proposed Rulemaking.

The analysis utilized the detailed operating characteristics and interference criterion of the UWB location system employed in iRobot's FCC certified Terra™ autonomous lawnmower, and the operational characteristics of Wi-Fi 6 routers deployed in residences and used for streaming 4K video.

The UWB location system that was analyzed, utilized UWB channel 5 with a bandwidth of 499.2 MHz and center frequency at 6.4896 GHz. Characteristics of the unlicensed Wi-Fi routers were consistent with the operating parameters proposed in the 6 GHz NPRM: power level up to 1 W conducted power and 6 dBi antenna gain, equivalent to EIRP of +14 dBm/MHz for 160 MHz channels, and wide deployment consistent with ubiquitous indoor residential use. The analysis showed that Wi-Fi 6 routers streaming 4K video created interference sufficient to disrupt up to 35% of the UWB ranging signals operating in UWB channel 5 if the Wi-Fi traffic is distributed over all existing and proposed unlicensed channels in 5 and 6 GHz, and the wireless router utilization is 10%. Even at 2% router utilization, 10% of UWB ranging signals are disrupted. Since the proposed high-power unlicensed service will disrupt existing authorized unlicensed UWB devices, if the FCC would like to preserve innovative UWB systems in the 6-7 GHz bands, it is recommended that the proposed rules be reconsidered to allow coexistence between UWB and Wi-Fi.

# 7 APPENDIX

## 7.1 Link Budgets

The arrangement of a UWB victim receiver with a single AP interfering transmitter is shown in Figure 7. Separate link budgets describe the links for the Desired and Interference signals.

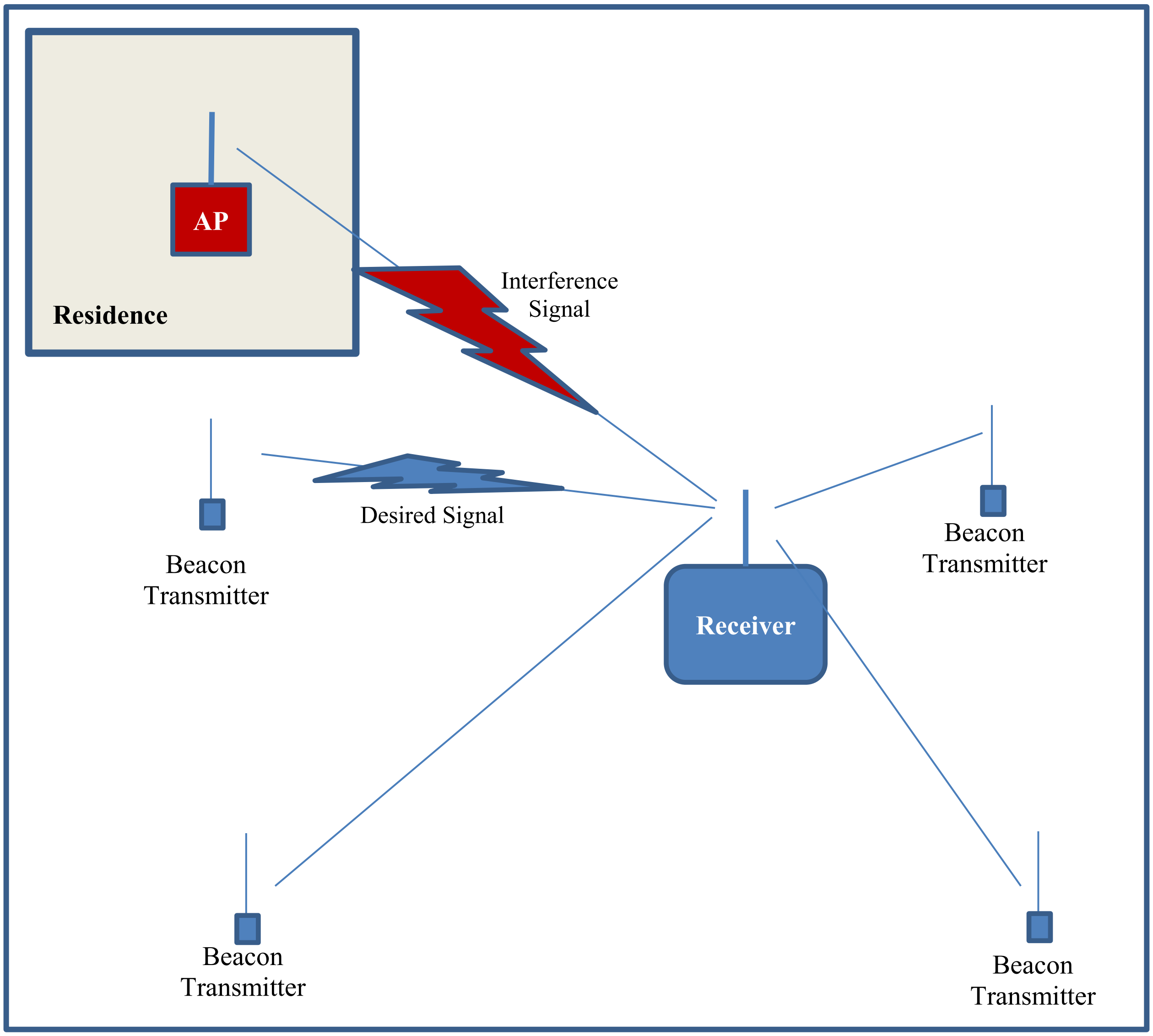


Figure 7 Transmitter and Receiver Arrangement

The link budget for the desired signal shows the transmit power, path losses, and received power for a signal. The path loss will generally depend on the distance and any obstacles in the path. There is also a link budget for interference that shows the transmit power of the interference, path losses to the victim receiver, and the received interference at the victim receiver.

The link budgets for the desired and interference signals at the victim receiver are shown in Table 3. The tabulated line items are described following the table. The link budget shows that a typical indoor AP will interfere with an outdoor victim UWB receiver at a distance of 50.5 meters.

Table 3 Link Budgets

| Desired Signal | | | Interference Signal | | |
|---|---|---|---|---|---|
| TX Power | 0.02 | mW | TX Power | 1000 | mW |
| | -16.99 | dBm | Bandwidth | 499.2 | MHz |
| Bit Rate | 6.81 | MHz | | | |
| | | | $N_{AP}$ | 1 | |
| TX $E_b$ | -25.32 | dBm/MHz | TX PSD | 3.02 | dBm/MHz |
| | | | E[BEL] | 11.00 | dB |
| TX Antenna Gain | 2.50 | dBi | TX Antenna Gain | 0.00 | dBi |
| D | 44.6 | m | D | 50.5 | m |
| fc | 6.4896 | GHz | Model | NLOS | |
| $\lambda$ | 4.62 | cm | $\lambda$ | 4.62 | cm |
| $L_{path}$ | 81.68 | dB | $L_{path}$ | 106.33 | dB |
| RX Antenna Gain | 2.50 | dBi | RX Antenna Gain | 2.50 | dBi |
| RX $E_b$ | -102.00 | dBm/MHz | RX Interference PSD | -111.81 | dBm/MHz |
| k | 1.38E-23 | J/K | | | |
| T | 300 | K | | | |
| B | 1.00E+06 | Hz | | | |
| F (noise factor) | 1.6 | | | | |
| | | | $I/N_0$ | -0.02 | dB |
| $N_0$ | -111.79 | dBm/MHz | $I+N_0$ | -108.79 | dBm/MHz |
| $E_b/N_0$ | 9.79 | dB | $E_b/(I+N_0)$ | 6.79 | dBm/MHz |
| Sensitivity | 6.78 | dB | $N_{rise}$ | 3.00 | dB |
| Margin | 3.01 | dB | Margin | 0.01 | dB |

TX Power – Conducted transmit power.

For the Desired signal this is transmitted in 500 MHz so that it results in a power spectral density of -41.5 dBm/MHz with the transmitter antenna gain. This is below the FCC limit for EIRP of -41.3 dBm/MHz.

For the Interference signal this is the maximum power in U-NII-5 and U-NII-7 permitted in the proposed rules.

Bit Rate – The UWB ranging application operates at an average bit rate of 6.81 Mbps. The transmitter spreads this signal over the 500 MHz bandwidth specified for UWB channel 5.

TX $E_b$ – Average energy per bit that is transmitted. The $E_b$ parameter is used for easy comparison to theoretical $E_b/N_0$ curves for BPSK modulation that are available in the technical literature. The $E_b$ is computed as the ratio of transmit power to the bit rate.

TX PSD, Bandwidth, $N_{AP}$ – The interference transmit spectral density is computed as the average power of each transmitter multiplied by a factor for the number ($N_{AP}$) of interfering transmitters, and divided by the Bandwidth of the victim receiver. This represents an average interference power spectral density incident upon the victim receiver.

E[BEL] – Expected Building Entry Loss. The Building Entry Loss (BEL) follows the ITU-R Rec. P.2109-2017 standard[31] for predicted building entry loss. The Expectation function averages a Monte Carlo simulation of the losses for the distribution of buildings in the standard. The Desired

[31] ITU-R Recommendation P.2109-0, *Prediction of building entry loss*, June, 2017 (Rec. P.2109).

path does not have any BEL, while the Interference path does have building entry loss for the indoor APs.

TX Antenna Gain – Transmitter antenna gain relative to an isotropic antenna. Note that the TX antenna gain for the Desired transmitter and Interference transmitter are not necessarily the same.

D, fc, $\lambda$ – Distance for the propagation path, center frequency for the UWB transmitter / receiver, and the corresponding wavelength ($\lambda$ = c/fc). The path distances for the Desired and Interference paths are not necessarily the same.

$L_{path}$ – Path loss for the Desired signal is: $L_{path} = 20 \log_{10}(4 \pi D/\lambda)$. This is the Free Space Path Loss (FSPL) model. The Non-Line-of-Sight (NLOS) model used for Interference includes some scattering effects for terrain. The Line-of-Sight (LOS) model is used for the outdoor AP transmitter.

RX Antenna Gain – Receiver antenna gain relative to an isotropic antenna. This is the antenna gain for the victim receiver. Omni-directional antennas are used for the victim receiver to permit it to receive from desired Beacon transmitters in any azimuth direction. This necessarily means that the antenna gain is the same for both the Desired and Interference signals.

RX $E_b$ – Received average energy per bit:

RX $E_b$ = TX $E_b$ + TX Antenna Gain – $L_{path}$ + RX Antenna Gain.

RX Interference PSD – Received interference power spectral density:

RX Int. PSD = TX PSD + TX Antenna Gain – E[BEL] – $L_{path}$ + RX Antenna Gain.

K, T, B, F – Receiver figures of merit for the noise floor. K is Boltzmann's constant. T is the noise temperature in Kelvin. B is the bandwidth for the power spectral density, which is 1 MHz in this calculation. F is a multiplicative noise factor for the receiver, often expressed in dB as an additive noise figure.

$N_0$ – Receiver power spectral density noise floor. $N_0 = 10 \log_{10}(k\ T\ B\ F)$. This is the denominator in the $E_b/N_0$ ratio for customary BER curves according to Shannon's information theory. The $N_0$ value is also used as an interference threshold in the simulation.

$E_b/N_0$ – Receiver energy per bit divided by the noise power spectral density for comparison to a sensitivity threshold.

Sensitivity – This is the sensitivity threshold $E_b/N_0$ to obtain acceptable receiver BER performance.

Margin – The Margin is the difference between the received $E_b/N_0$ and the Sensitivity threshold. Positive margins permit the receiver to work, while negative margins cause the receiver to fail. The parameters for the Desired signal have the distance, D, adjusted for a Margin of +3 dB without interference. The parameters for the Interference have the distance, D, such that the Margin with Interference is near 0 dB. This degrades the Margin without interference of +3 dB by the 3 dB value expressed in section 4.1

$I/N_0$ – Interference to Noise ratio in the victim receiver. The distance parameter, D, for the Interference has been adjusted so that the $I/N_0$ ratio is near 0 dB, indicating that the interference power is equal to the noise floor in the receiver.

$I + N_0$ – Sum of the power spectral density for the interference and noise floor. This is a sum of powers, so the I and $N_0$ parameters in units of dBm/MHz are converted to mW/MHz, then summed, and then converted back to dBm/MHz units.

$E_b/(I+N_0)$ – This is the ratio of the received energy per bit to the sum of the interference and noise powers.

$N_{rise}$ – Noise rise in the receiver. This expresses in dB the additional apparent noise in the victim receiver from interference. In dB units: $N_{rise} = (I + N_0)_{dB} - (N_0)_{dB}$.

## 7.2 Path Loss Models

Models for Path Loss ($L_{path}$) include Free Space Path Loss (FSPL), Line-of-Sight (LOS), and Non-Line-of-Sight (NLOS) path loss. The FSPL model is the basic formula given in textbooks as a function of the path distance, D, and the wavelength of the electromagnetic wave. The wavelength is determined by the speed of light and the frequency. If D and λ use the same units, their ratio will be dimensionless.

$$FSPL = 20 \log_{10}(4 \pi D/\lambda) \text{ in dB} \qquad \text{with } \lambda = c/f \qquad \text{Eq. 6}$$

The LOS model given in Equations 7a and 7b, depends on antenna heights, $h_1$, and $h_2$. A break-point distance, $d_{break} = 4 h_1 h_2 / \lambda$. For $D<d_{break}$, use Equation 7a. For $D \geq d_{break}$, use Equation 7b.

$$LOS = 22 \log_{10}(D) + 28 + 20 \log_{10}(f) \qquad \text{Eq. 7a}$$

$$40 \log_{10}(D) + 7.8 - 18 \log_{10}(h_1 h_2) + 2 \log_{10}(f) \qquad \text{Eq. 7b}$$

with D, $h_1$, and $h_2$ given in meters and f in GHz
and $h_1$, $h_2$ are the antenna heights of the transmitter, receiver.

The LOS and NLOS models are given in ITU-R Report M.2135[32], Table A1-2 for Urban Micro Cell scenarios. The same LOS and NLOS channel models are also used in IEEE-802.11 Simulation[33] for the scenarios for 802.11ax.

$$NLOS = 36.7 \log_{10}(D) + 22.7 + 26 \log_{10}(f) \qquad \text{Eq. 8}$$

with D given in meters and f in GHz

The height of the AP antennas was set to 2 meters and the UWB receiver antenna height was 0.5 meters. The adjustment suggested in the 802.11 Simulation to subtract 1 meter from the access point and mobile device antenna heights was not used.

## 7.3 Building Entry Loss

Building Entry Loss (BEL) is predicted in Rec. P.2109. The recommendation gives a BEL Cumulative probability Distribution Function (CDF) that varies with frequency and elevation angle. In this application the elevation angle is zero, and the frequency is 6.5 GHz. The recommendation has two CDF functions, one for Traditional buildings and another for Thermally Efficient buildings. The Traditional CDF function is used here, as shown in Figure 8.

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[32] ITU-R Report M.2135-1, *Guidelines for evaluation of radio interface technologies for IMT-Advanced*, December, 2009 (Rep. M.2135).

[33] IEEE 802.11-14/0980r16, *Simulation scenarios for the 11ax TG*, November 2015, (802.11 Simulation).

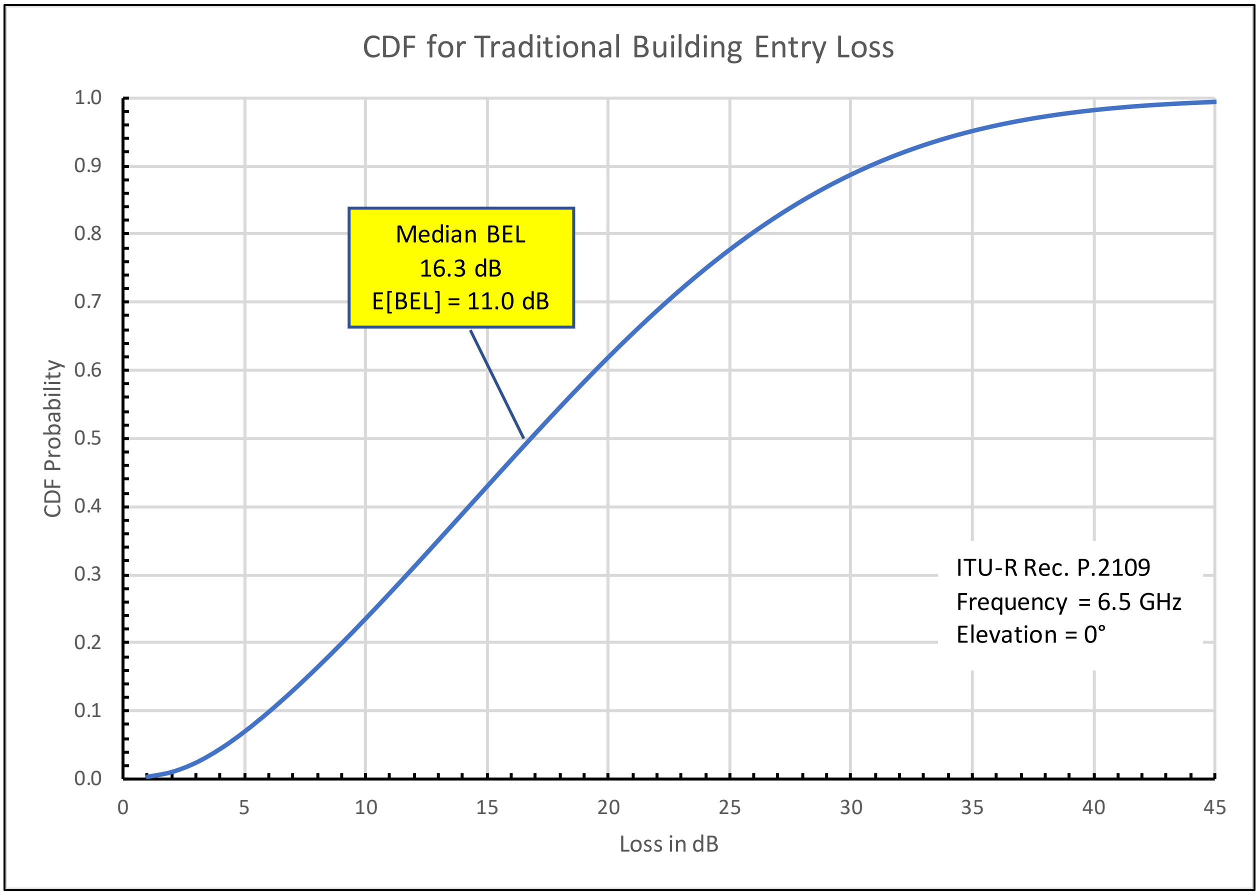


Figure 8 Cumulative Probability Distribution of Building Entry Loss

## 7.4 Simulation Detailed Results

The Monte Carlo simulation included AP transmitters in a 7x7 grid representing a typical array of residential lots, each with an area of ¼ acre (=1000 $m^2$) as shown in Figure 5. The victim UWB receiver was placed randomly in the center lot and interfering AP transmitters were placed randomly in the residences. The AP traffic was adjusted according to conditional parameters for the percentage of APs with video traffic and the duty cycle of the video traffic. A Monte Carlo trial resulted in interference if one or more AP transmissions overlapped in time and frequency with the 3 ranging packets at the victim UWB receiver, and the AP transmission(s) power exceeded the interference power threshold, as shown in Figure 4. The results for one condition are shown in the following Figure 9.

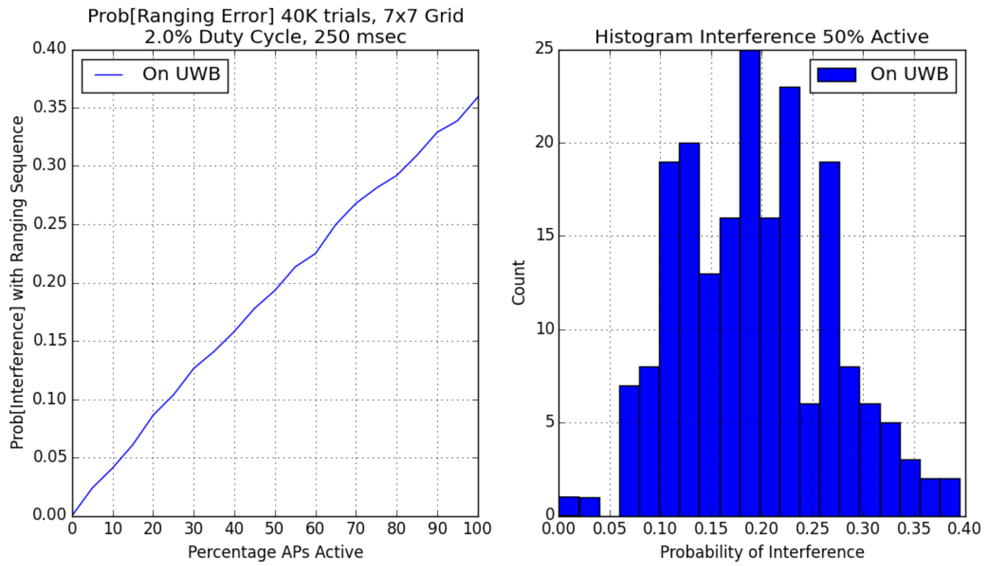


Figure 9 Probability of Interference for 2% Duty Cycle and Wi-Fi Traffic Channels Overlapping UWB Channel 5

Figure 9 shows a graph on the left for the simulated probability of interference as a function of the active APs. The active APs are set to transmit at a 2% duty cycle. The probability of interference increases from zero up to 36% as the AP activity increases to 100%.

The histogram on the right shows the probability distribution for the 50% AP activity condition. The average value in the histogram is 20%, coinciding with the graph on the left at 50% APs Active. Even though the average probability of interference is 20%, this varies in each neighborhood according to the random distribution of APs, and the histogram shows that this can increase to 39% probability of interference in a few neighborhoods out of the 40,000 in the simulation. In this particular condition, all the APs are constrained to the 3 Wi-Fi channels that overlap UWB channel 5 (see Figure 1).

The average probability of interference can also be plotted for all the conditions on a surface, as shown in the following Figure 10.

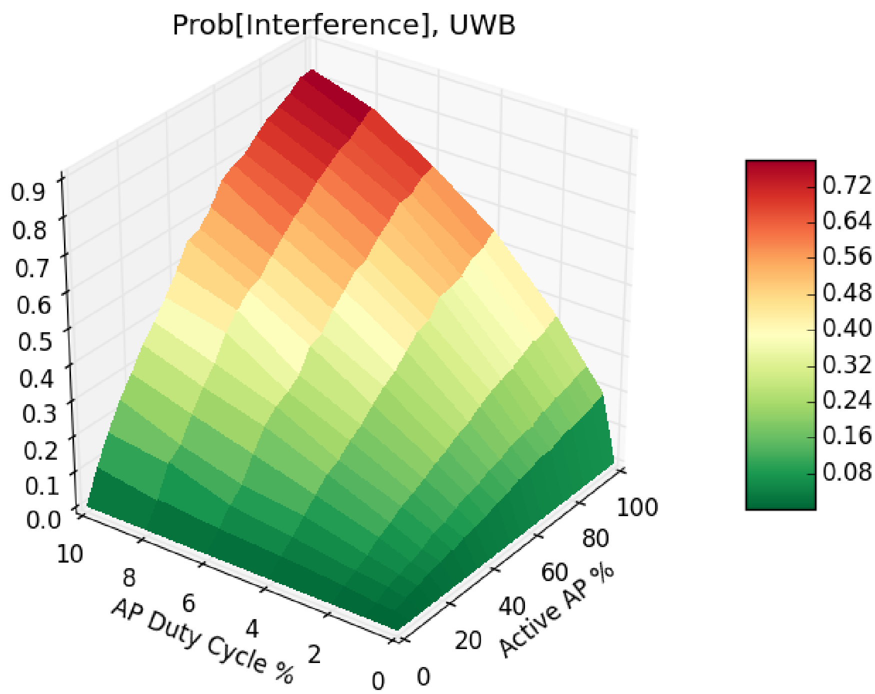


Figure 10 Probability of Interference for Wi-Fi Traffic Channels Overlapping UWB Channel 5

Figure 10 shows the average probability of interference over all the conditions for AP duty cycles up to 10% and AP activity up to 100%. The probability of interference increases up to 80% for the maximum duty cycle and AP activity. This graph still concentrates all the AP traffic in the 3 Wi-Fi channels overlapping UWB channel 5.

An additional simulation distributed the AP traffic over 11 channels in the 5 and 6 GHz bands. The corresponding probability of interference is shown in the following Figure 11.

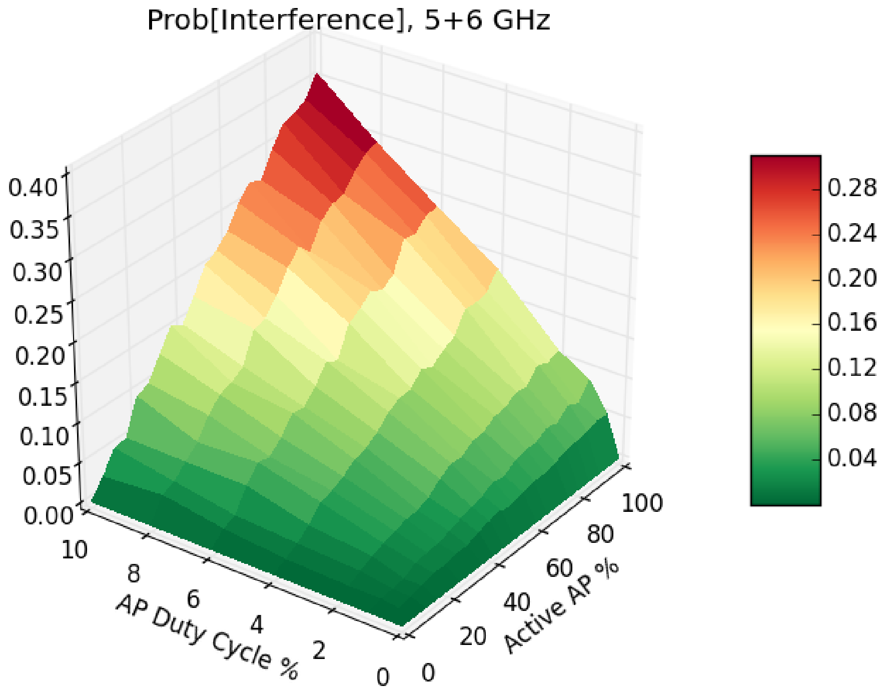


Figure 11 Probability of Interference for Wi-Fi Traffic Distributed in all 5 and 6 GHz U-NII Bands

Figure 11 shows the average probability of interference over all the conditions for AP duty cycles up to 10% and AP activity up to 100%. The AP traffic is distributed across the 5 GHz and 6 GHz bands, so less traffic overlaps UWB channel 5, and the probability of interference is reduced, relative to the previous Figure. The probability of interference increases up to 35% for the maximum duty cycle and AP activity. This figure is also reproduced in section 5.6 to summarize results of the simulation.

# 8 Company Profile: Roberson and Associates, LLC

Roberson and Associates, LLC, is a technology and management consulting company serving government, commercial, and academic customers and provides services in the areas of radio frequency (RF) spectrum management, RF measurement and analysis, strategy development, and technology management. The organization was founded in 2008 and is composed of a select group of individuals with corporate and academic backgrounds from Motorola, ARRIS, Bell Labs (AT&T, Bellcore, Telcordia, Lucent, and Alcatel-Lucent), BroadView Communications, Cisco, Department of Defense (DARPA), DePaul University, Google, IBM, Illinois Institute of Technology (IIT), Illinois Institute of Technology Research Institute (IITRI), Illinois Tool Works (ITW), Massachusetts Institute of Technology (MIT), NCR, Nokia, S&C Electric, Vanu, Inc., and independent consulting firms. Together, the organization has over 1,000 years of high technology management and technical leadership experience with a strong telecommunications focus.